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An aircraft encounter with a tornado

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Summary

The loss of an aircraft near Rotterdam on 6 October 1981 was attributed to an encounter with a tornado. Evidence supporting this claim is presented, followed by a discussion of the associated meteorological situation. A rough estimate of the probability of encounter with a tornado is given and some aspects of the use of radar in detecting and forecasting severe storms and tornadoes are briefly described.

1. Introduction

At 1604 GMT on 6 October 1981, a Fokker F-28 aircraft (PH-CHI) took off from Rotterdam *en route* to Eindhoven. There were thunderstorms in the area and the aircraft, flying at 3000 ft (900 m), entered one of them a few minutes after take-off. After a short period of moderate turbulence in cloud, the aircraft suddenly encountered extreme turbulence in which the starboard wing was detached and, at 1612 GMT, the aircraft crashed near Moerdijk, about 25 km south-south-east of Rotterdam, with the loss of all occupants.

It soon transpired that a tornado was reported just west of Moerdijk a few minutes before the crash, and in fact a police launch travelling east along the Hollandsch Diep had not only taken a series of photographs of the tornado, but also — less than a minute later — of the cloud of smoke rising from the aircraft impact explosion. This, together with other evidence provided by the Director of the Aeronautical Inspection Directorate of the Dutch Civil Aviation Authority showed that it was very likely that the aircraft encountered the tornado circulation in cloud shortly after the tornado funnel had lifted from the ground.

The flight safety implications raised by this incident led the Dutch and British Civil Aviation Authorities to ask the United Kingdom Meteorological Office to assess the probability of a tornado encounter in flight, and whether it was necessary or possible to make special arrangements to forecast tornado conditions.

Since, as far as we are aware, this is the only case of an aircraft encounter with a tornado whilst in flight for which it so happened that adequate evidence was available, the Dutch Civil Aviation Authority agreed that an account of the incident should be published after the findings of the official enquiry were released.

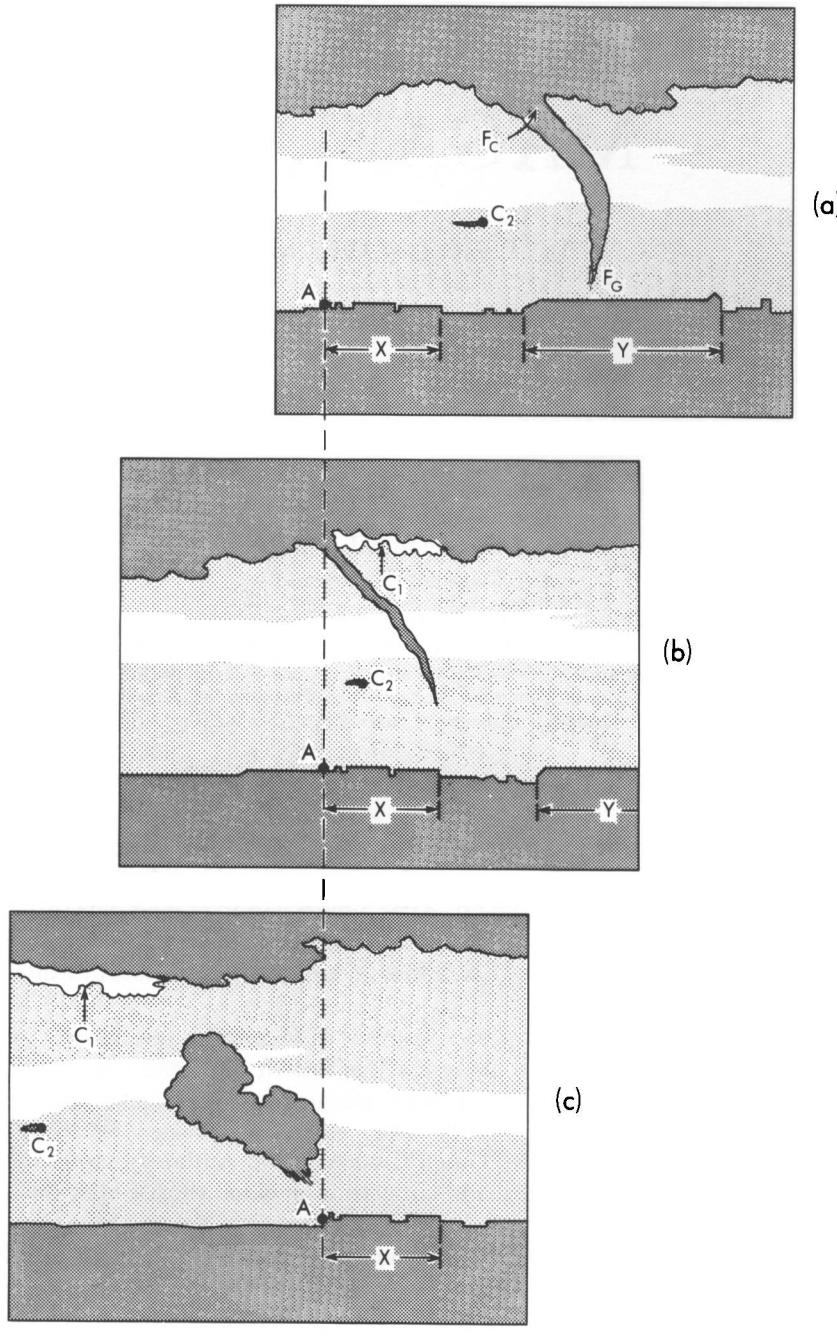

Figure 1. Drawings based on photographs 1, 8 and 16 of the series taken from the police launch. The labelling is explained in the text. Fig. 1(c) shows the cloud of smoke ejected from the aircraft crash. The corresponding photographs are shown on the facing page.

There are three parts to the account: the first presents and discusses the evidence that the aircraft did encounter a tornado circulation; the second discusses the meteorological situation; and the third presents an estimate of the probability of aircraft–tornado encounter in the United States and in north-west Europe.

2. The evidence for tornado encounter

The evidence for encounter of the F-28 aircraft with a tornado is based on the following material kindly provided by the Dutch Civil Aviation Authority:

(a) Fifteen prints of the Moerdijk tornado and two prints of the aircraft explosion cloud taken by a police launch on the Hollandsch Diep. (See Fig. 1.)

(b) Two colour prints of the same tornado from another site a few minutes earlier.

(c) A 1:10 000 scale map of the Moerdijk area indicating the aircraft track, the location of the police launch and the position from which the colour photographs were taken, with direction lines. Also indicated is the tornado track based on surface damage. (See Fig. 2.)

(d) A copy of the flight record recovered from the aircraft wreckage. (See Fig. 3.)

(e) Hourly maps of radar echo distribution for the period 1300–1700 GMT on 6 October 1981.

Unfortunately, but not surprisingly, the times of the photographs were not recorded. However, the lateral movement of cloud features C_1 and C_2 relative to a fixed ground point A (Figs 1(a) and (b)) enabled a relative time scale to be assigned to the police launch prints. Confidence in this procedure is given by a plot of the coordinates of C_1 and C_2 against each other which shows an almost perfectly straight line (correlation coefficient 0.997) (Fig. 4). Also plotted against C_2 are the coordinates of the bottom (F_G) and the visible top (F_C) of the tornado funnel. These show rather more scatter about a straight line, but indicate that the tornado circulation as a whole was moving at a roughly constant speed.

C_1 and C_2 are also identifiable on the prints of the aircraft explosion cloud. Backward extrapolation of the two explosion cloud images enables a time of aircraft–ground impact to be located on the relative time scale (Fig. 4) within fairly narrow limits.

The colour photograph direction lines drawn on the Moerdijk map yield an angular calibration on these photographs of 0.037 radians per centimetre from which it appeared that the width of the tornado funnel near cloud base was about 100 m and decreasing, and the height of cloud base was about 400 m. The tornado damage path indicated in the map was over 300 m wide and showed that the funnel cloud marks the centre of a much bigger circulation.

There were no direction lines drawn for the police launch photographs, and it proved difficult to identify surface features appearing on the prints with those on the map. However, the images of the tornado and associated cloud are of similar size on both colour and police launch photographs, and were taken from a similar distance (about 2 km). Using this fact, it appears that building complexes X and Y on the photographs (Fig. 1) were probably those marked X and Y on the map (Fig. 2), and this has been assumed in the subsequent analysis. The point A marking the left of the building complex X on Fig. 1 was directly in line with the aircraft impact point, and is thought to correspond with the point A on Fig. 2.

The location of the centre of the tornado circulation at the time of aircraft–ground impact is estimated to lie near α on Fig. 2, and is obtained by extrapolating the line F_C to the impact point on the relative time scale in Fig. 4.

Evidence from the flight recorder, (Fig. 3) has been used to estimate the location of the aircraft along its track at 5-second intervals relative to time of impact as marked in Fig. 2.* The accelerometer record

*For the purpose of this estimate, ground speed was assumed equal to indicated air speed corrected for descent angle. Corrections for wind (outside the tornado circulation) and for air density are of the order of 5% and are neglected.

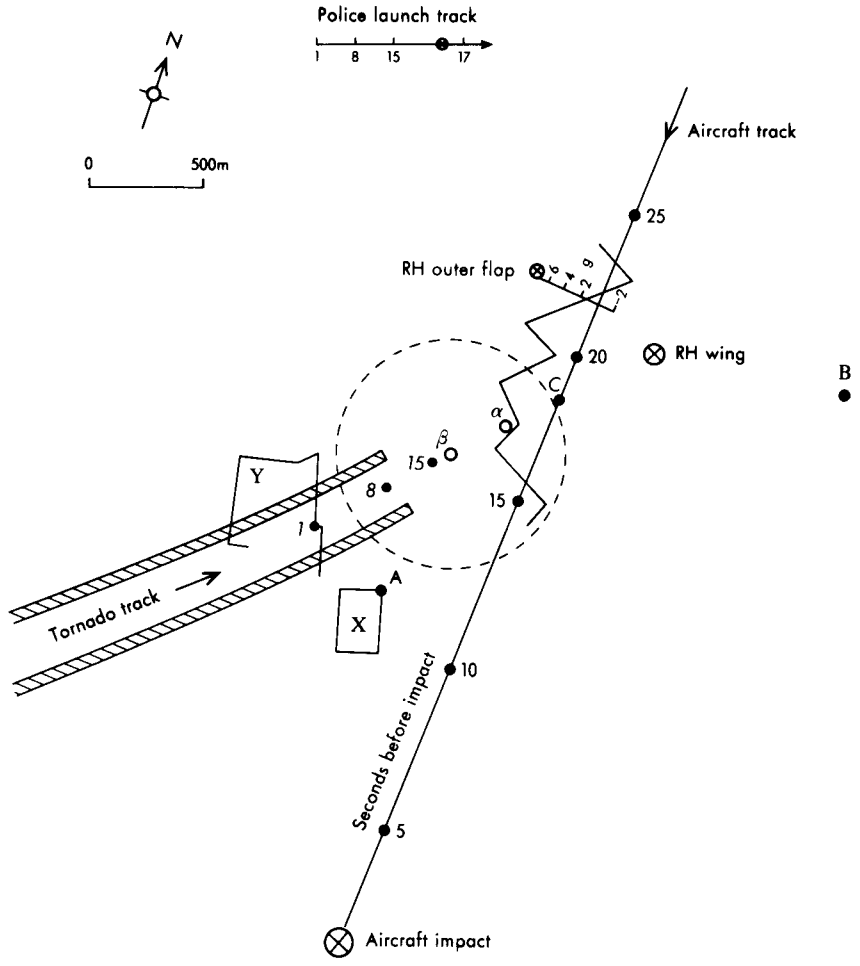

Figure 2. Sketch map of tornado and aircraft tracks. Labelling is explained in the text.

has been superimposed on the aircraft track in Fig. 2. The main '*g*-spikes' are close to the intersection of the aircraft track with the projected tornado track (C in Fig. 2) about 18 seconds before impact, and to the position of impact of the starboard wing and flap, while the disturbance in which the *g*-spikes are embedded appears to have affected about 1 km of the aircraft track. However, C appears to be ahead of the estimated centre of the tornado circulation (α) when the aircraft crashed 18 seconds later. The location of this circulation at the time the aircraft was at C cannot be directly estimated as the speed of the tornado is not known and the relative time scale (Fig. 4) has not been calibrated. However, there are indirect indications:

(a) The sequence of radar pictures (one of which is shown in Fig. 14) show that the storm complex which passed over the site of the accident was moving north-east at about 20 m s^{-1}. It is likely that the tornado circulation was being carried by the storm complex at about the same speed.

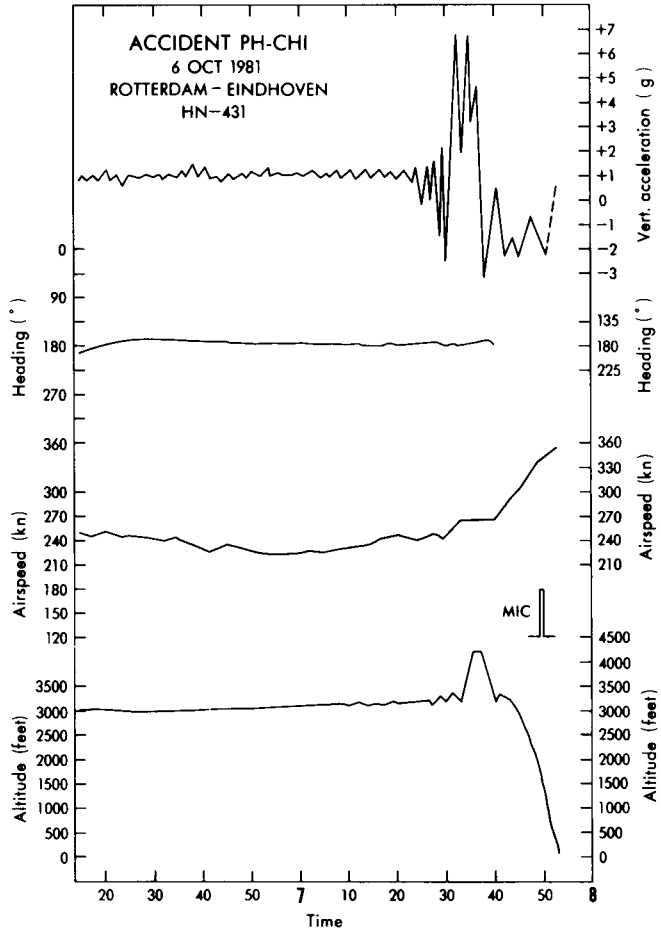

Figure 3. Copy of part of the flight record recovered from the crashed aircraft. Time is in minutes and seconds from take-off.

(b) Reference to Fig. 2 shows that the funnel cloud was moving about 50% faster than the police launch. The inferred speed of 13 m s^{-1} for the police launch seems fast if photographs were being taken from it, but it may have been trying to 'keep up' with the funnel. We consider that the speed of translation of the tornado circulation was about 15 m s^{-1}.

The estimated position of the centre of the tornado circulation when the aircraft was at C (Fig. 2) is probably within 200 m of β. A circle of 500 m centred on β intersects the aircraft track during the latter part of the most disturbed part of the g-trace. Hence it appears that the aircraft probably encountered the tornado circulation and crashed as a result.

Finally, the temporary indicated height increase of about 300 metres, due to a recorded decrease of pressure of 29 mb, immediately after the main g-spike is of interest. This may be partly real owing to the large vertical velocities usually associated with tornado circulations, and partly spurious owing to the drop of pressure within the tornado and/or rapid attitude changes of the aircraft after or during the detachment of its wing creating anomalous aerodynamic effects at the altimeter orifice.

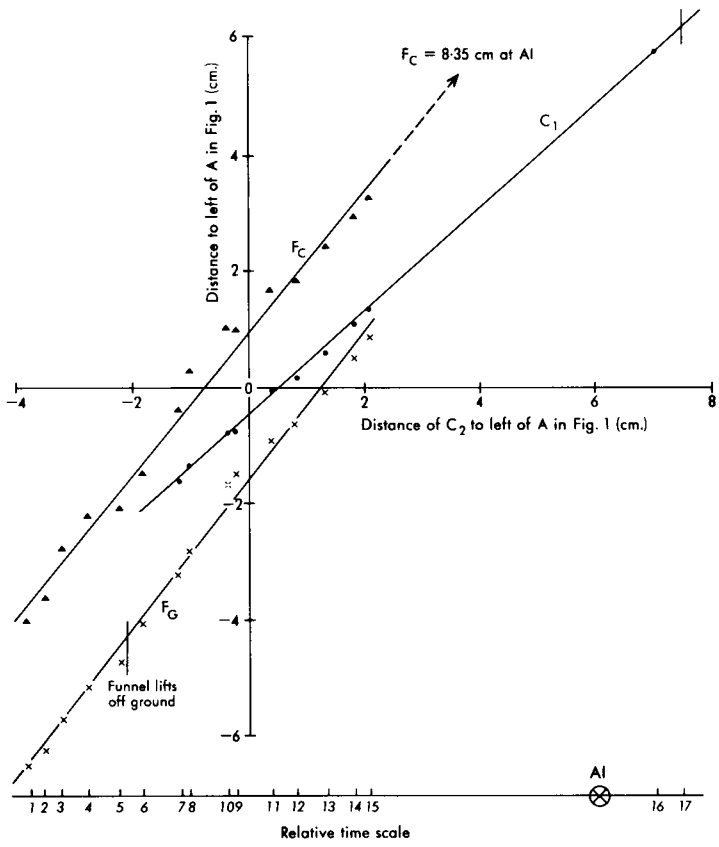
F_C = 8·35 cm at A1
C_1
F_C
F_G
Distance to left of A in Fig. 1 (cm.)
Distance of C_2 to left of A in Fig. 1 (cm.)
Funnel lifts off ground
A1
Relative time scale

Figure 4. Establishment of a relative time scale using the police launch photographs. Explanation is given in the text.

3. The meteorological conditions

3.1 *General situation*

At 1200 GMT on 5 October 1981 a small depression was approaching the north of Ireland from the west whilst a diffuse warm or quasi-stationary front lay close to the line Lisbon–Paris–Cologne. This front, originally of double or complex structure, was analysed in differing forms and positions by different meteorological centres. In this report, however, it is considered to be the genesis of a warm front since it developed more pronounced characteristics as warm advection set in over the continent of Europe. A depression west of Portugal induced a wave on the front which developed and moved north-eastwards to become centred in the English Channel by 1200 GMT on 6 October. Meanwhile the associated warm front advanced northwards across Europe, passing over most of the Netherlands between 0600 and 1800 GMT. The cold front of the same depression moved quickly across the Bay of Biscay and France, and passed over the Netherlands between 1500 and 2000 GMT.

Subsequently, the wave depression moved over the North Sea and amalgamated with the Atlantic depression which had become slow moving near the north of Scotland. Fig. 5 shows the general synoptic situation at 1200 GMT on 6 October 1981 and the depression tracks as given in the relevant *Daily Weather Summary* of London Weather Centre.

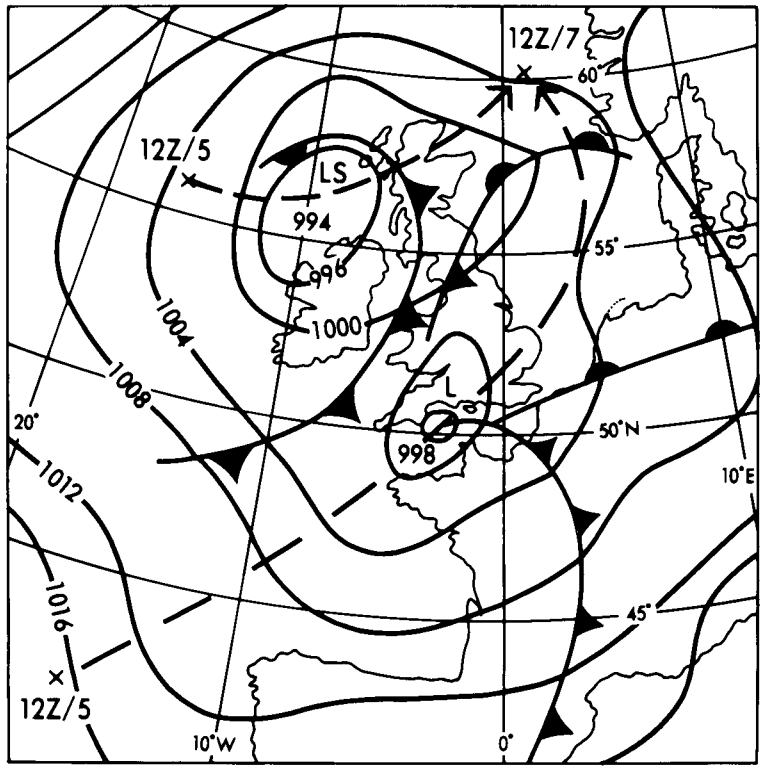

Figure 5. Synoptic situation at 1200 GMT on 6 October 1981.

3.2 *Surface charts*

Hourly surface charts from 1200–1800 GMT have been analysed in detail but only those for 1200, 1500 and 1800 GMT are reproduced in Figs 6-8. By 1500 GMT (Fig. 7) rain associated with the warm front had cleared from the Rotterdam area which was then covered by a light southerly flow of warm moist air with dew-point temperatures of 15–16 °C. The cold front was advancing rapidly from the west at about 26 m s^{-1} preceded by outbreaks of thundery rain and thunderstorms. Observational evidence indicates that the area of thundery activity ahead of the cold front was typified by generally stronger surface winds, a reduction in the fall of pressure and a distortion in the surface pressure field. The characteristics suggest that cold air was overrunning the surface cold front in the lower levels. There is insufficient evidence to place the upper cold front precisely, and indeed it may have been a diffuse feature, but what evidence there is, and considerations of continuity between the hourly analyses, indicate that the overrunning cold air extended to 90 km or more ahead of the surface feature. The surface and upper cold front positions are shown in Figs 6-8 and the hourly positions and speeds of these fronts are shown in Fig. 9; this shows that the upper cold front, heralding the arrival of thunderstorms, crossed the accident site at approximately 1545 GMT and the surface cold front passed the same site at about 1640 GMT bringing clearing weather.

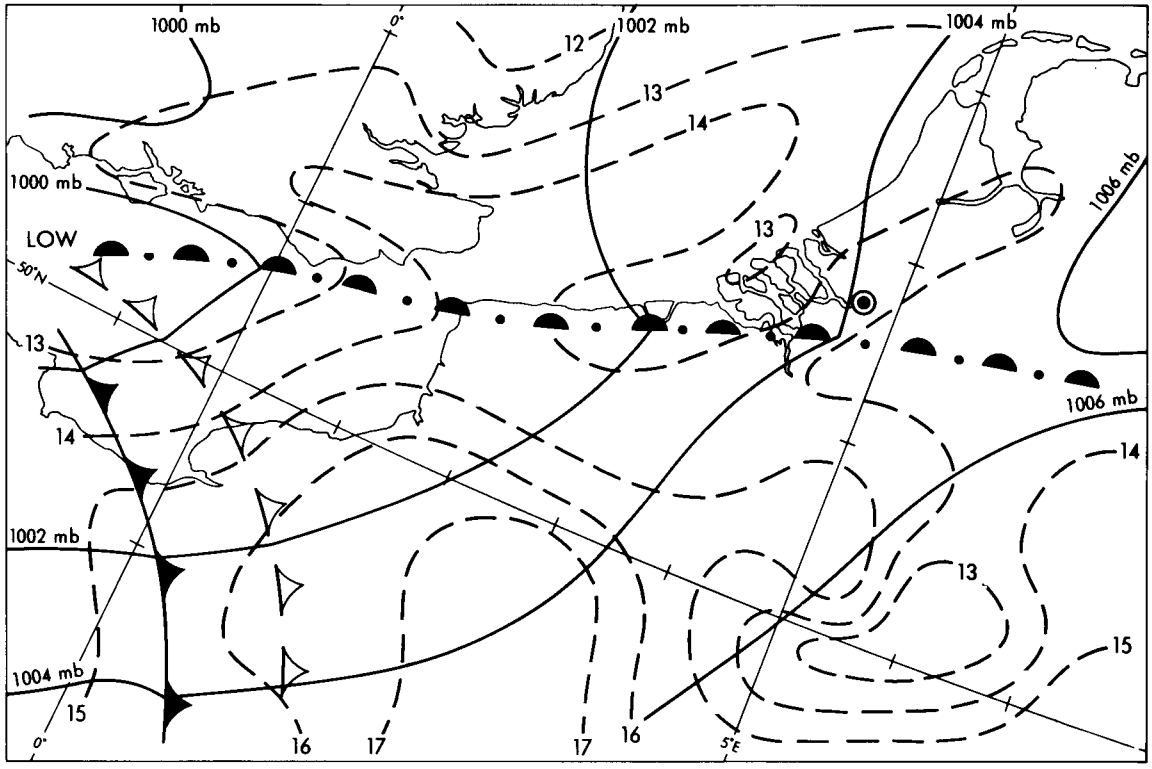

Figure 6. Surface analysis for 1200 GMT on 6 October 1981, showing distribution of wet-bulb potential temperature (θ_w) at the surface.

3.3 *Upper-air charts*

At 1200 GMT on 6 October 1981 a major upper trough lay to the west of the British Isles with a strong jet stream on its eastern flank. At 300 mb the jet axis was from the south-west over central France with a speed of 50 m s^{-1}. At 500 mb and 700 mb the speeds on the jet axis were 37 m s^{-1} and 30 m s^{-1} respectively. At 700 mb and 850 mb the jet displayed several axes. Fig. 10 illustrates the jet axes at 850 mb with speeds of 22–27 m s^{-1} and Fig. 11 shows the sounding made at Trappes at 1200 GMT. A feature of particular interest at 850 mb is the very strong cyclonic shear zone lying along the coasts of France and Belgium and extending to the western part of the Netherlands at 1200 GMT.

An analysis of 850 mb wet-bulb potential temperature, (θ_w), also shown in Fig. 10, indicates the position of the northward-moving warm front and, less markedly, the cooler and drier air over France behind the cold front. The geometry of the analysis between Paris and Brussels indicates some intrusion of the cooler and drier air ahead of the position of the surface cold front at this time preceded by a tongue of somewhat warmer and moister air. Values of θ_w at the surface level near Paris and the area to the north-east were typically 16–17 °C in south-south-westerly winds of 10 m s^{-1} or less whilst at 850 mb air from the south-west with the value of θ_w at Paris of 13 °C was penetrating overhead at more than 20 m s^{-1}. It is unfortunate that no upper-air sounding at 1200 GMT was made in the zone between the two fronts to confirm the marked potential instability, and latent instability, which must have been building up in the area north and north-east of Paris at this time, though the Trappes ascent was made just ahead of the upper, probably diffuse, cold front and indicates some of the characteristics of the zone.

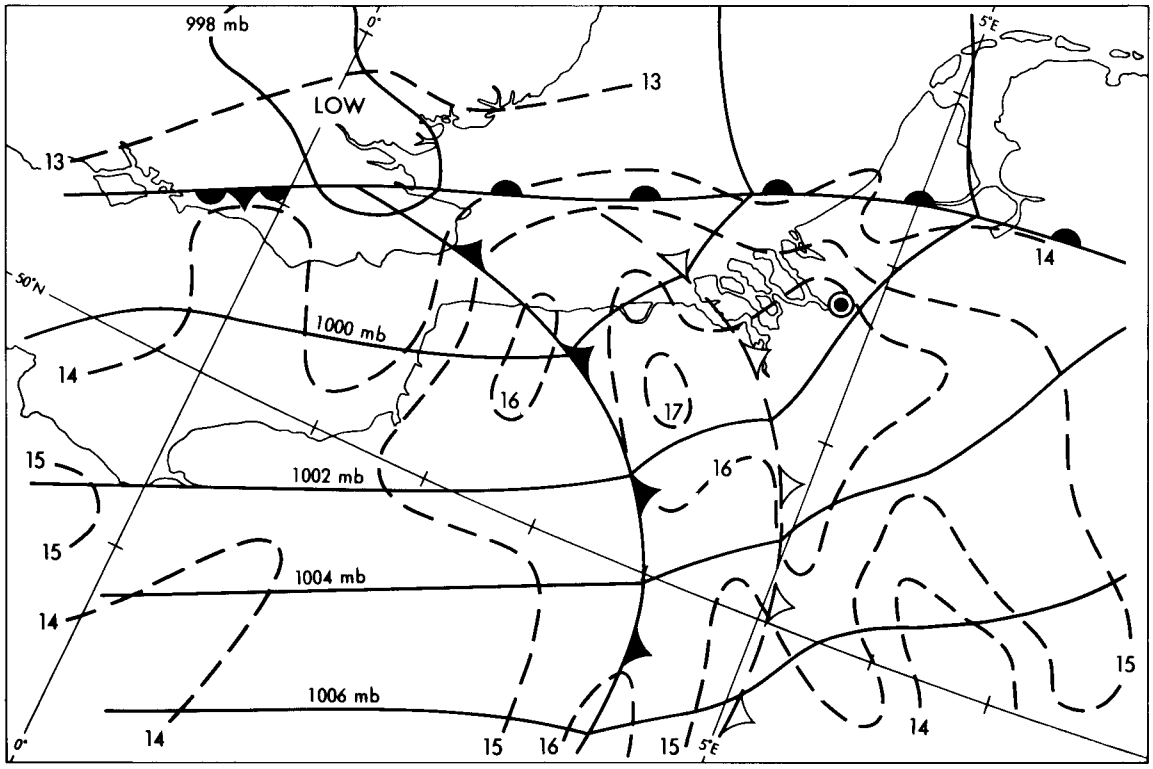

Figure 7. As Fig. 6 but for 1500 GMT.

3.4 *Autographic records*

The only relevant autographic records near the observed tornado track or the scene of the accident were from an anemograph situated at an air pollution monitoring station at point B in Fig. 2. A reproduction of the records of surface wind direction and speed is shown in Figs 12(a) and (b). The wind speed in the original record is shown as a series of dots at short time-intervals but this record has been simplified in Fig. 12(b) by showing lines denoting maximum, mean and minimum wind speeds only.

The record shows increasing wind speeds between 1535 and 1545 GMT with a gradual veer of surface wind from east of south to a little west of south, probably due to the downward transfer of momentum from the increasing south-westerly winds above the surface as the upper cold front passed. A second increase in wind speed occurred between 1640 and 1650 GMT and the wind veered to a westerly at 1650 GMT as the surface cold front passed. Between these two events lighter surface winds of about 4–7 m s^{-1} obtained and marked directional changes took place. These directional changes are analysed in Fig.12(c) and sketched streamlines suggest that a tornado cyclone (see Fujita 1959) passed the station between 1612 and 1622 GMT disturbing the generally south-westerly wind field, and that a cyclonically rotating vortex passed a few hundred metres to the north of the anemometer site at 1619 GMT. It has been shown earlier that the aircraft intercepted the tornado circulation in cloud within a minute of 1612 GMT when the tornado funnel had lifted from the surface. The assumed speed of that tornado, though dissipating at the surface, would have placed it a few hundred metres to the north of the anemometer site at about 1613–1614 GMT some 5–6 minutes earlier than a vortex was deduced to have passed there.

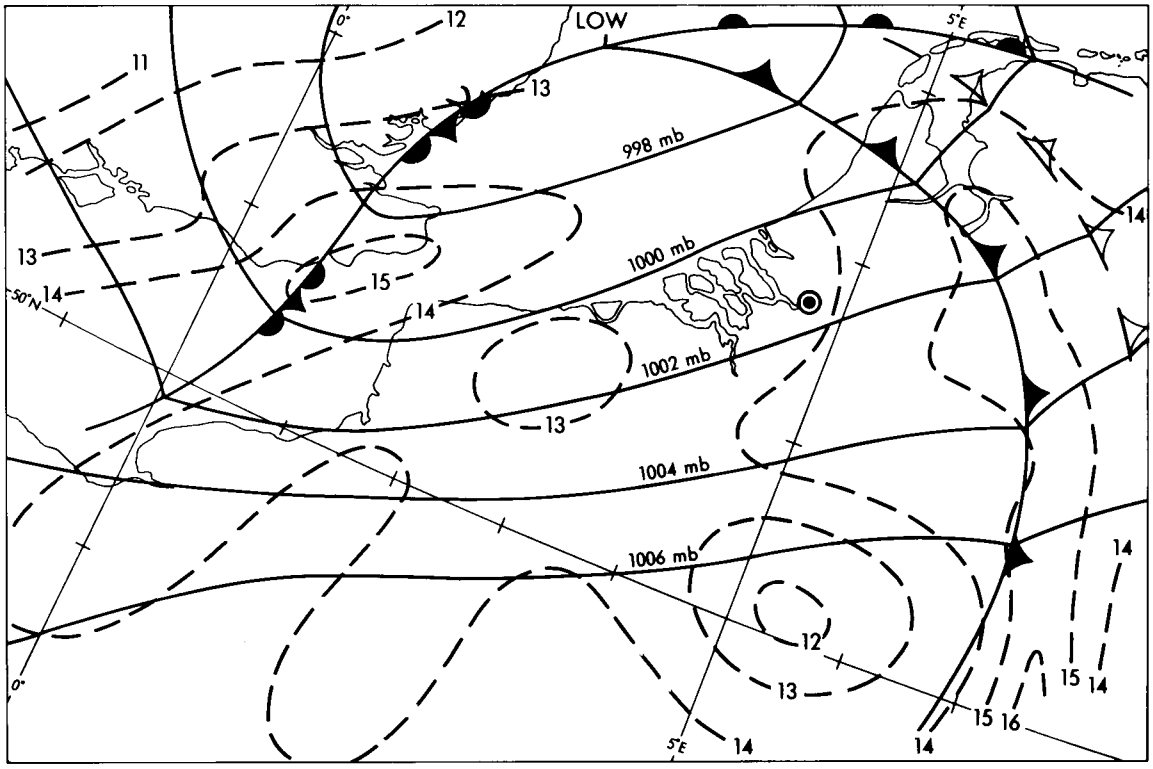

Figure 8. As Fig. 6 but for 1800 GMT.

However, there may be an error in the timing of the anemograph record or there may have been more than one tornado or vortex in the wider area of the tornado cyclone. Indeed, eyewitnesses, and one photograph, give evidence of two tornado funnels in the area just before the accident.

3.5 *Discussion*

Potential instability produced in the zone between the surface and upper cold fronts by differential advection was released mainly by lifting due to convergence in the area. Surface wind convergence was pronounced in a discrete area shown in Figs 13(a), (b) and (c) and the area of maximum convergence passed close to the accident site shortly after 1500 GMT (Fig. 13(b)). The positions of surface wind reporting stations used to compute divergence and vorticity are shown by dots in Fig. 13.

The development of convergence was associated with a zone of cyclonic vorticity lying along the coast of continental Europe into the southern North Sea (Figs 13(d), (e) and (f)). A line of maximum vorticity can also be discerned in association with the cold fronts, and this line passed across the accident site with the cold fronts. It can be deduced that the area and line of maximum cyclonic vorticity resulted in surface convergence which in turn contributed to the release of potential and latent instability. The instability extended through a deep layer as shown by the reporting of thunderstorm activity by the United Kingdom Sferic (atmospheric) network. This activity was remotely located at 1200 GMT in an area of approximate radius 65 km over northern France and located hourly until 1800 GMT. Hourly positions of the centre of this area are shown in Fig. 9 and it is evident that this area was centred somewhat behind the upper cold front and ahead of the surface cold front. The centre of the area passed between

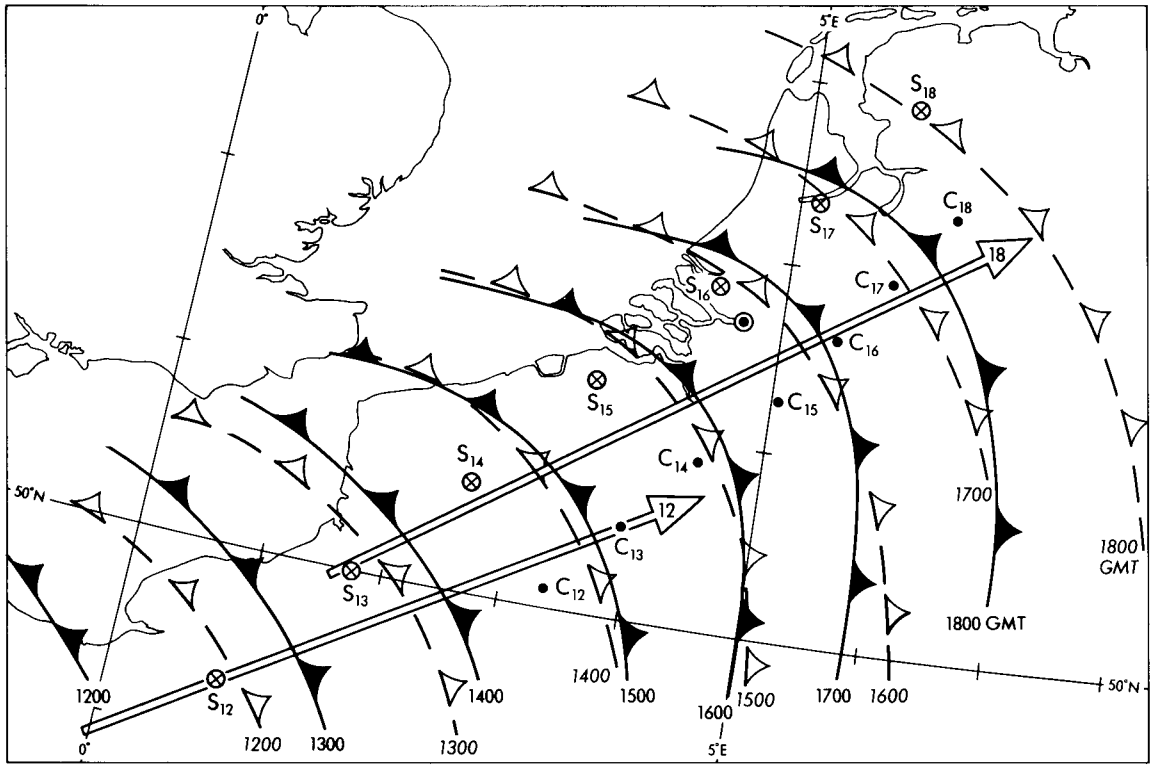

Figure 9. Continuity chart, 6 October 1981.

Upper cold front

Surface cold front

S_{hh} Centre of Sferic (thunderstorm) activity at hour hh (GMT) (Radius of active area 65 km approximately)

C_{hh} Position of maximum surface wind convergence at hour hh (GMT)

hh Jet axis at 850 mb at hour hh (GMT)

Accident site

Rotterdam and the accident site at about 1600 GMT and one of the radar images from De Bilt at this time is shown in Fig. 14, on which the frontal positions have been superimposed. The position of the jet axis at 850 mb at the same time, interpolated from the 1200 and 1800 GMT positions shown in Fig. 9, is also included in Fig. 14. The centre of the area of maximum convergence passed to the south-east of the accident site between 1500 and 1600 GMT. Three-hourly positions and interpolated hourly positions are included in Fig. 9.

The radar images taken from De Bilt at hourly intervals indicated that the organized thunderstorm cells associated with the area between the surface and upper cold fronts were moving at about 25 m s^{-1} past the south and east of the accident site, whilst those passing to the west and north of the site were travelling at about 17 m s^{-1}. Since the accident site lay on the northern flank of the jet axis at low level in the zone of pronounced cyclonic shear, and hence in a region of cyclonic vorticity, upward motion and

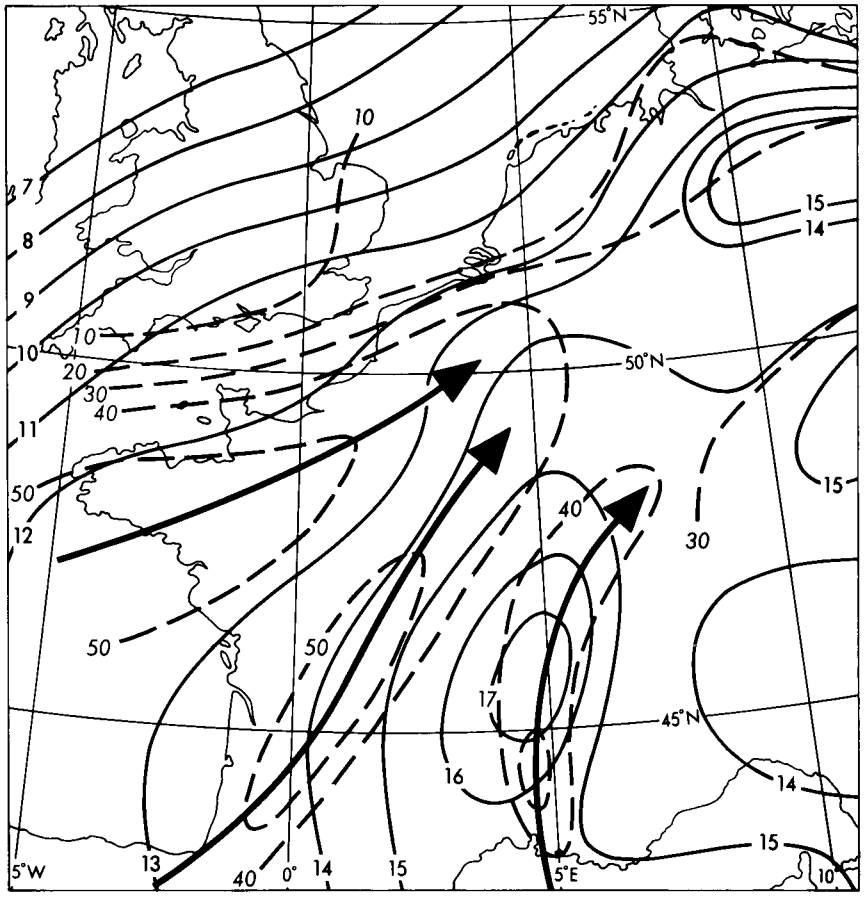

Figure 10. Selected streamlines and isotachs (dashed lines) of 850 mb flow at 1200 GMT on 6 October 1981. θ_w at 850 mb is indicated by continuous lines. (Isotachs are in knots; 1 kn = 0.5148 m/s^{-1})

the subsequent release of latent heat and potential instability would further locally intensify the low-level convergence and lead to the concentration of cyclonic vorticity with which tornadic storms are associated. In these circumstances tornado cyclones form, with diameters typically of 5–40 km, and may contain one or more actual tornadoes.

It was reported that a hook-shaped radar echo was visible on a photograph of the De Bilt radar image at 1600 GMT in the southern part of the large echo which adjoins the accident site in Fig. 14. No precise position or size has been given for this significant echo and it cannot be discerned on the radar tracing in Fig. 14. However, hook-shaped radar echoes have often been reported in the United States just prior to the appearance of surface tornadoes, and the dimension (along the wind) of 13 km of the tornado cyclone deduced from Fig. 12 and the dimension (across the wind) of 14 km of the swath of damage of tornado funnel sightings at Moerdijk, Hellegatsplien, Ridderkerk and Puttershoek to Hendrik Ido Ambacht, provide very strong evidence of the presence of a tornado cyclone on this occasion.

It has been suggested by several authors (e.g. Browning and Ludlam (1962), Browning (1965a, b), Browning and Atlas (1965), and Carlson and Ludlam (1968)) and by experience, that the formation of organized severe local storms requires that several conditions should be satisfied. These are:

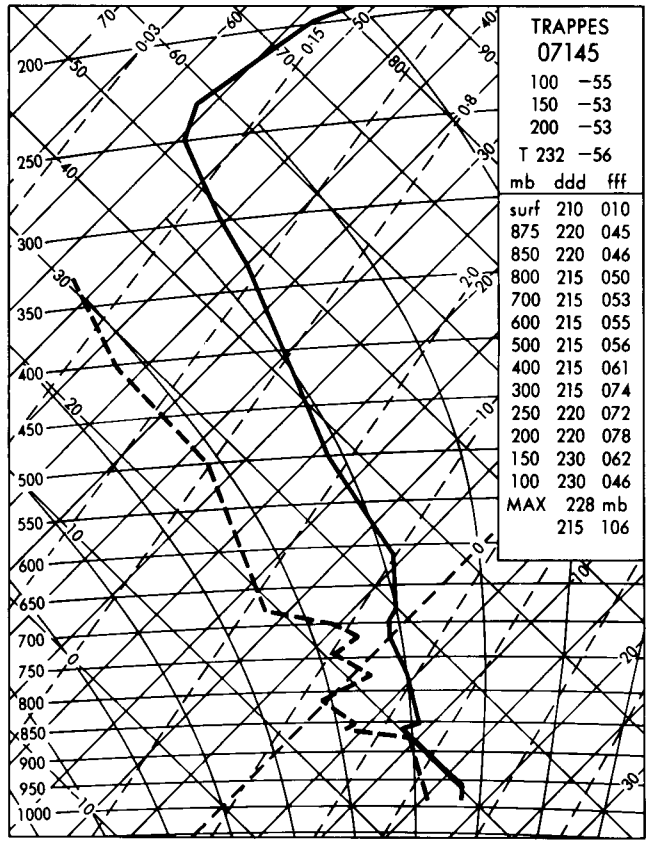

Figure 11. Upper-air sounding from Trappes (France) at 1200 GMT on 6 October 1981. Wind speeds (fff) are given in knots (1 kn = 0.5148 m s^{-1}).

(a) A supply of warm moist air at low levels. The possibility of severe storms should be considered if θ_w exceeds about 15 °C, but cannot be ruled out at lower values of θ_w.

(b) Great depth of instability.

(c) Great buoyancy indicated by a large excess of surface or low-level θ_w over the saturation wet-bulb potential temperature (θ_s) in the middle or upper troposphere.

(d) Vertical wind shear extending from a jet stream of about 50 m s^{-1} at 300 mb down through the convective layer with strong directional shear of the order of 15 m s^{-1} between the surface and 850 mb levels (intense warm advection) is particularly favourable for storm formation.

(e) Trigger action by daytime surface heating, low-level convergence, or orographic uplift.

(f) Northward advection of air warmed over Europe, especially Spain, may form a lid to small-scale convection such that low-level moisture is confined beneath it and high buoyancy can develop before it is finally released.

The meteorological conditions upwind of the accident site prior to that event correspond well with these criteria. Surface values of θ_w in excess of 16 °C had spread into the Netherlands by 1500 GMT (Fig. 7) and a great depth of real latent instability was evident from the upwind Trappes sounding at 1200 GMT near the upper cold front, where θ_w at the surface was 17 °C and θ_s at 500 mb was 14 °C (Fig. 11).

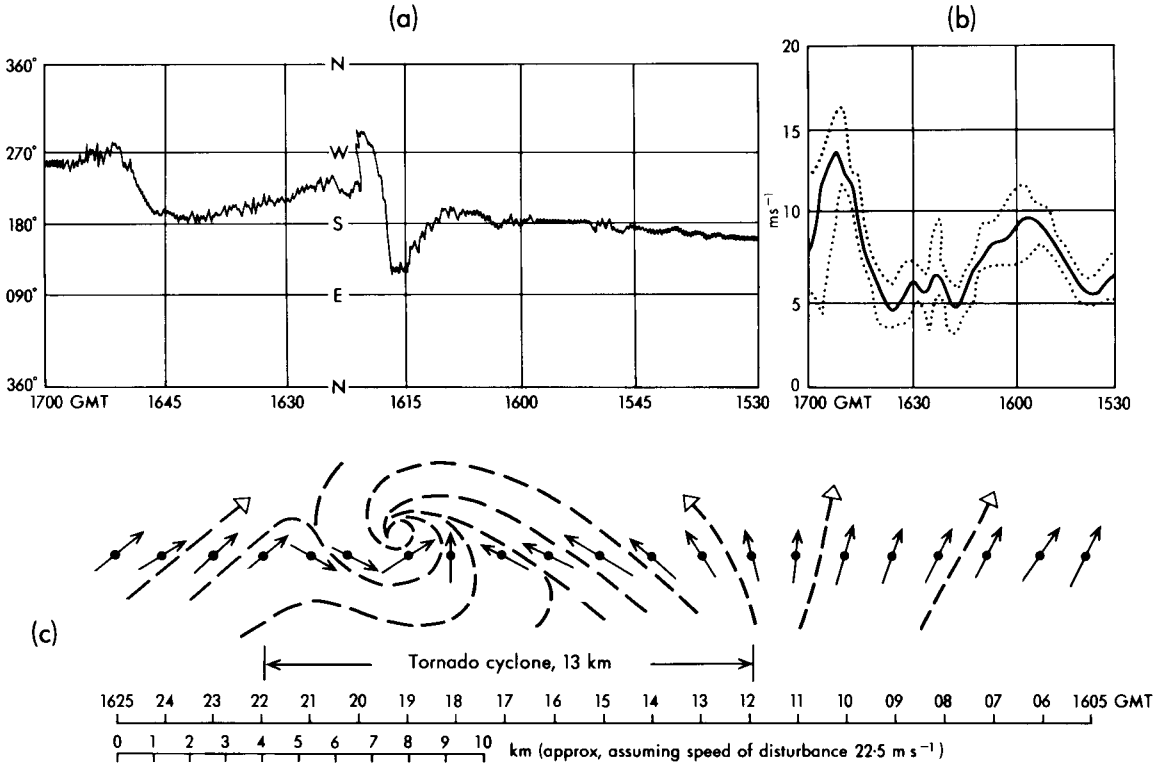

Figure 12. Anemogram traces (a), (b) from air pollution monitoring station at Moerdijk on 6 October 1981 and the deduced airflow (c) in the vicinity. The site of the anemometer is at point B in Fig. 2.

Also, pronounced low-level warm advection was taking place and the shear between the winds at the surface (240°, 5 m s^{-1}) and 850 mb (220°, 23 m s^{-1}) at Trappes was 18 m s^{-1}. With surface winds over the Netherlands at 1500 GMT of 180°, 7 m s^{-1} and 850 mb winds of 240°, 22–24 m s^{-1} penetrating into the area (240°, 27 m s^{-1} at De Bilt at 1800 GMT) the shear in the lowest 150 mb was at least 20 m s^{-1} in the vicinity of the accident site. Daytime heating and pronounced low-level convergence were present to release the instability. The instability may have been suppressed earlier in the day by the shallow stable layer evident at Trappes at 1200 GMT between the levels of 860 and 853 mb.

It may be concluded that the air mass between the surface and upper cold fronts was favourable for the development of severe convective storms, and it was especially so in the area bounded in the south by the axis of the jet stream at 850 mb and in the north by the coastline on the edge of the strong upper winds at 850 mb.

4. Estimated probability of aircraft–tornado encounter

4.1 *Background*

Climatological tornado statistics in the United States are used to estimate the frequency of encounter in the 'worst' tornado areas, and are then related to the (rather small) amount that is known about UK tornadoes. It is assumed that tornado occurrence over south-east England is roughly representative of that over low-lying parts of north-west Europe. The basic method is as follows:

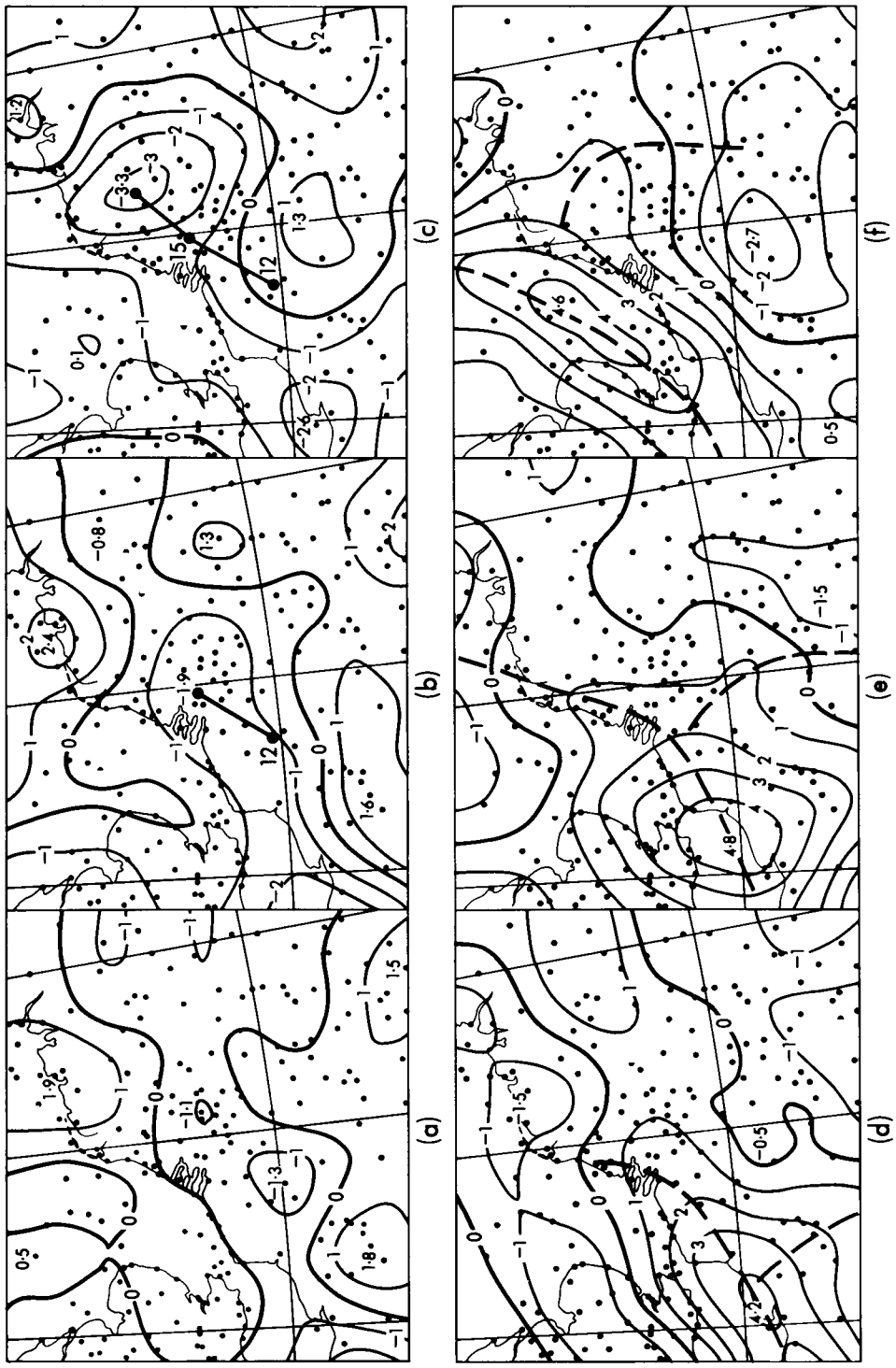

Figure 13. Surface wind divergence and vorticity on 6 October 1981.
Divergence at (a) 1200 GMT, (b) 1500 GMT, (c) 1800 GMT
Vorticity at (d) 1200 GMT, (e) 1500 GMT, (f) 1800 GMT
Units: 10^{-5} s^{-1}

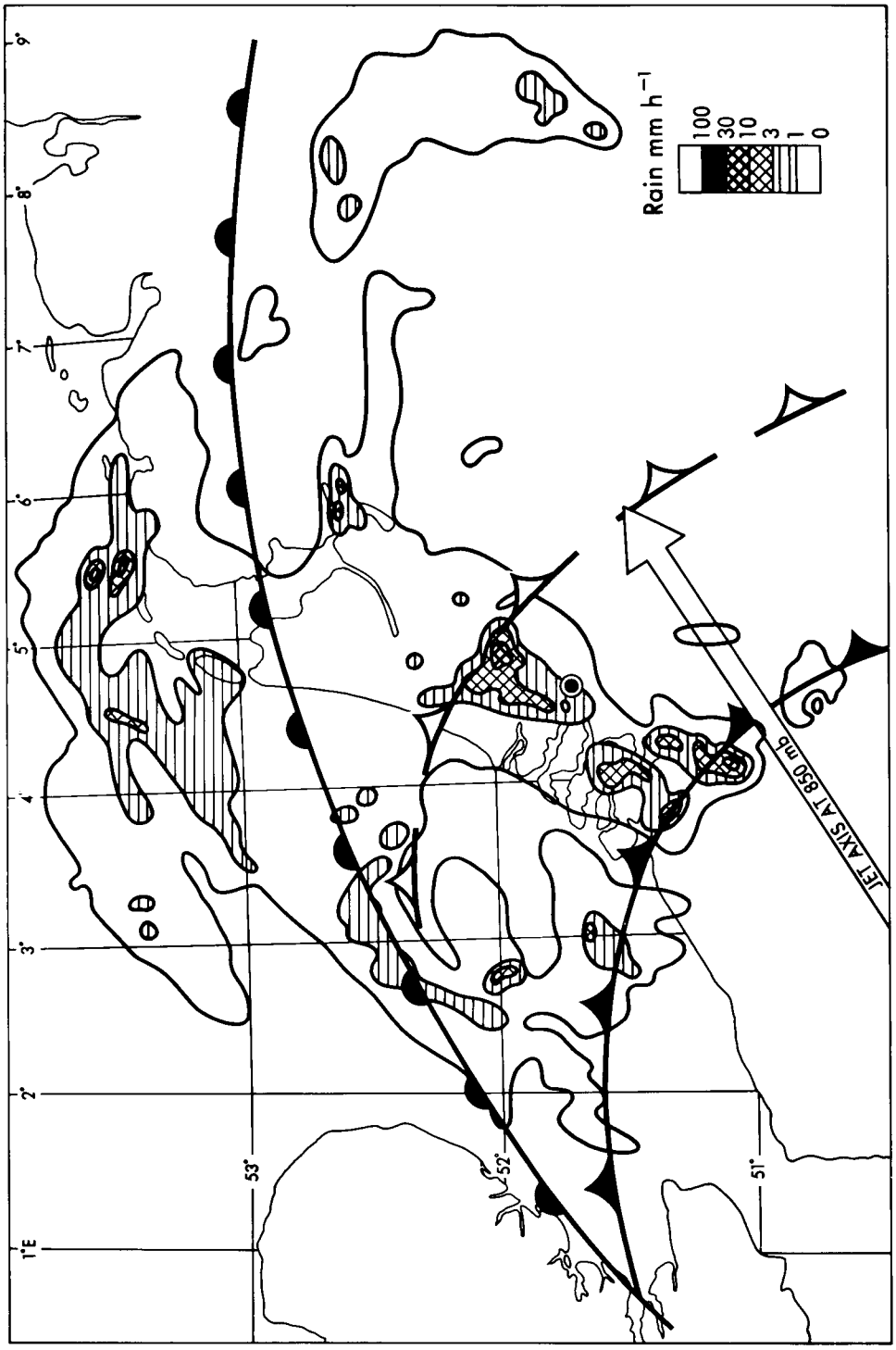

Figure 14. Radar images of rain areas recorded at De Bilt at 1600 GMT on 6 October 1981. Frontal positions and the jet axis at 850 mb are superimposed.

(a) *Return period.* From the statistics of tornado frequency and size distribution now available in some quantity from the United States, it is possible to estimate the return period (T) of a tornado at a given point. If the statistics for a given point apply over a fairly large area, then an aircraft flying over the area will encounter a tornado about once in period T.

(b) *Tornado frequency and damage area.* There is a range of some 4 to 5 orders of magnitude in the damage area produced by one tornado. About 90% of tornado damage in the United States is caused by the relatively few large tornadoes — typically at least 300 m in diameter and with path length greater than about 15 km. In the United Kingdom tornado frequency per unit area per year is comparable to that in the United States (Fujita 1973), but the associated damage area is far less.

(c) *Vertical extent of tornado circulation.* Tornadoes are spawned by meso- or tornado-cyclones which are intense circulations up to a few kilometres in width generated by the thunderstorm circulation. These circulations can be detected in cloud by Doppler radar up to half an hour before the associated tornado touches down. There is some evidence that the most intense circulation in a developed tornado occurs 100–200 m above the ground, and above this the vortex widens and the wind speeds decrease somewhat. Nevertheless, there is now evidence (Lemon *et al.* 1982) that the tornado circulation may extend through most of the depth of the storm and constitute a hazard to aircraft at all heights in the storm, including possibly those storms that spawn funnel clouds which do not reach the ground. Thus frequency of aircraft encounter based on surface damage area may result in some underestimate.

4.2 *Computation*

(a) *United States.* Tornado frequency in the United States is highest in the mid-west states (Tecson and Fujita 1979) with totals over the period 1916–78 approaching 200 per 10^4 km^2.

Fujita and Pearson (1973) have characterized tornado intensity by a three-dimensional scale of wind speed, path length and path width. These three properties are usually well correlated and it is sufficient in practice to use one scale of intensity — the F-scale. The distribution of tornadoes over the F-scale is given in Table I.

Table I. *Distribution of United States tornadoes.*

F-scale	0	1	2	3	4	5
Frequency (%)	22	34.5	29	11	3	0.5
Damage area (km^2)	0.0025	0.025	0.25	2.5	25	250

This yields an average of 2–2.5 km^2 of damage area per tornado which, multiplied by a frequency of 3 per 10^4 km^2 per year gives a damage area of about 7 km^2 per 10^4 km^2 per year, or a return period (T) of $10^4/7$ — about 1400 years — implying one aircraft encounter per 1.3×10^7 flying hours. This result is comparable with that given by Hill and Johnson (1982). This Table is uncorrected for the increasing efficiency of reporting of the smaller tornadoes over the last two decades. Correction for this increases tornado frequency, but reduces mean damage area per tornado and so has little effect on aircraft encounter probabilities.

(b) *United Kingdom.* There is much less evidence available from the United Kingdom, but enough to make some estimate. It appears (Lacy 1968, Meaden 1976) that the annual frequency of reported tornadoes ranges from 5 to 60 with an average of 20 to 30. Practically all of these occur east and south of the mountains of Wales and northern England. This corresponds to a frequency of 1 per 10^4 km^2 per year, increasing to a maximum of about 5 in the home counties area. This is comparable to the worst area of the United States, but UK tornadoes rarely exceed an intensity of $F2$. Meaden (1976) reports that the frequency of tornadoes of intensity ≥ 4 on the Meaden scale (corresponding to about $F2$) is a maximum

in the Midlands of about 20% of the total frequency. In order to assign an F-scale to UK tornadoes, we note that the United States frequencies given in Table I fit a Poisson distribution quite well:

$$P(F) = \exp(-\bar{F}).\frac{\bar{F}^F}{F!},$$

where $P(F)$ = probability of tornado of intensity F and
$\bar{F}$ = mean intensity.

$\bar{F} \simeq 1.3$ gives a 'best fit' to the frequencies in Table I. Accordingly, a Poisson distribution with $\bar{F} = 0.8$ corresponds to 20% of tornadoes of intensity $F \geqslant 2$ and gives us Table II.

Table II. *Estimated intensity distribution of United Kingdom tornadoes.*

F-scale	0	1	2	3
Frequency (%)	45	36	15	4
Damage area (km^2)	0.0025	0.025	0.25	2.5

This gives an average area of 0.1–0.2 km^2 per tornado, implying a return period of the order of 15 000 years in the home counties area, or an aircraft encounter frequency of the order of once per 10^8 flying hours.

These figures are based on surface damage area, and are likely to be underestimated owing to broadening of the tornado circulation with height. We have little information on which to correct for this, but suggest that encounter frequencies should be increased by a factor of 3 to take crude account of it. This yields:

Frequency of aircraft–tornado encounter { United States / United Kingdom } once per { 10^6–10^7 / 10^7–10^8 } flying hours in 'worst' areas

The low-lying areas of France and Germany are climatologically not very different from south-east England, so that the above figures for the United Kingdom are probably fairly representative of much of the low-lying areas of north-western Europe.

The estimate for the United States suggests that tornado encounters 'ought' to be fairly frequent. An analysis of aircraft accidents by the National Transportation Safety Board (1978) shows that during the 3.6×10^7 hours flown by general aviation in 1976, 7 non-fatal accidents were partly or wholly attributed to 'local whirlwinds'. Moreover, 167 accidents (i.e. 5 per 10^6 flying hours) were also attributed to 'wind shear, turbulence in cloud/thunderstorm, downdraughts and updraughts, and thunderstorm activity'. It is possible that some of these accidents, particularly those in cloud, may have been associated with tornado cyclone circulations. Thus our estimate of tornado encounter frequency does not appear to be obviously misleading.

5. Conclusions

Evidence is presented which supports the claim that the loss of an aircraft near Rotterdam was due to an encounter with a tornado. The meteorological situation exhibited most of the features associated with tornado- and hail-generating storms of the United States. In addition, intense radar-echo complexes moving rapidly north-east are characteristic of severe organized storms often observed in the United States.

Severe storms in north-west Europe are too rare to warrant a special severe-storm forecasting service on the United States pattern, but there may be some merit in forecasters acquiring some familiarity with synoptic and radar features associated with severe storms, particularly those forecasters who will be using the UK Radar Network Display.

Lee (1967) reported a significant association between radar echo intensities of storm cores and the turbulence experiences on research aircraft flying through these cores. More recently (NOAA 1978) it has become possible to detect developing tornado cyclones within storms up to half an hour before the first tornadoes touch down. However, the prospects of detecting tornadoes by the plan display of the UK Radar Network are not good. Browning (private communication) writes:

> Tornadoes are associated with thunderstorms having intense echoes as seen on a plan display, but they often occur in the (right) flank of the echo away from the precipitation core. It is not very helpful to look for rapidly rising radar tops because some of the severest storms are already in a steady state, and in any case it is difficult to do a rapid volume scan to identify the rate of rise of individual tops. (Note that we do not obtain any vertical storm-top information in the UK weather radar network, but we do use Meteosat half-hourly infra-red imagery to spot high tops with rapidly expanding anvils.)
>
> Hook echoes are known to be unreliable indicators of tornadoes, even in the USA, since they are sometimes obscured by other echoes, especially at long range. At other times, fortuitous echo distortions may look like hook echoes to the untrained eye. In the UK, hook echoes are very rare and will not be seen by the current display resolution of 5 km.

It is the view of the authors that some service which alerts aviation to the possibility of severe storms and which might operate on a similar basis to that of the wind shear alerting service at Heathrow (but with access to a suitable radar display) would be better than no service at all.

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COMPSTAT 82

By R. C. Tabony

(Meteorological Office, Bracknell)

The COMPSTAT symposia on computational statistics are held under the auspices of the European section of the International Association for Statistical Computing, a branch of the International Statistical Institute. The first COMPSTAT meeting was held in Vienna in 1974, and since then they have been held every two years and gained a wide popularity. The 5th symposium was held at the Paul Sabatier University, Toulouse from 30 August to 3 September 1982, and brought together over 500 people whose main interest lay in the development and promotion of statistical software.

The conference was organized so that a day would begin with two invited speakers addressing an auditorium which contained seating accommodation for all. Thereafter a series of contributed papers, limited to half an hour each, were read in parallel in four lecture theatres. A display of posters was held in a large room, while a permanent exhibition was mounted in the main hall. All the major software enterprises were represented here, and gave continuous demonstrations of their packages and facilities. The majority of participants at the symposium were European, but there were also speakers from the USA, Australia and Japan.

The main concern of the conference was the development and improvement of packaged statistical software. All aspects were covered, from data-base management through exploratory data analysis to the latest statistical theory and numerical algorithms to use in packaged programs. Now that many packages contain a wide variety of statistical techniques, emphasis was placed on the need to design user-friendly systems, with easy data manipulation, good documentation, and clear presentation of results. The use and influence of micro- and array-processors in statistics, and the use of computers in teaching statistics, were also discussed. The only applications area considered lay in the fields of archaeology and history.

Many papers took the form of an advance in theory, or the introduction of a new algorithm, followed by its implementation in the form of saleable software. Other papers compared the strengths and weaknesses of the many packages now on the market and, to the writer, these were some of the most interesting presentations.

The writer's presence was due to a contribution on the estimation of missing data. This is a ubiquitous problem, and one which has not received the attention it deserves from the compilers of statistical packages. The BMDP suite* is one of the few packages to contain a program for estimating missing

*BMDP Biomedical Computer Programs, P-series. Health Sciences Computing Facility, Department of Biomathematics, School of Medicine, University of California, Los Angeles.

values, and I was given the opportunity of reporting its poor performance when applied to climatological data. There was little of this user feedback at the symposium, and more of it would have been very relevant to the aims of the gathering.

Much of the work of organizing the symposium fell on A. de Falguerolles, who acted as secretary to both the Organizing Committee, chaired by P. Ettinger, and the Scientific Program Committee, chaired by H. Caussinus. The Proceedings were edited by H. Caussinus, P. Ettinger and R. Tomassone. The policy of limiting each contributed paper to six pages ensured that each author concentrated on the main points of his argument, and this makes for easier reading than would otherwise be the case.

Notes and news

Retirement of Captain G. A. White

Captain G. A. White, Extra Master, retired from the Meteorological Office on 31 December 1982 after spending the past 13 years as Marine Superintendent and adviser to the Director-General on all matters concerned with the meteorological requirements of the mercantile marine.

When Gerald Arthur White joined the Office in 1969, he already had a long and varied career in the merchant navy behind him. This started in August 1941 when he became a cadet in the Canadian Pacific Steamship Company. Whilst he was transiting the Panama Canal on 7 December of that year it was rumoured that Japanese aircraft carriers were in the vicinity and likely to make an attack on the Canal. On arriving on the Atlantic side of the Canal word was received regarding Pearl Harbor. In the following August when homeward bound in the North Atlantic his ship was sunk by enemy action. In his next voyage he was again in a heavy convoy attack and, shortly after, when he was again outward bound, his second ship was torpedoed and sunk. Later he was in the first convoy to pass from Gibraltar to Port Said after the Mediterranean had been closed to allied shipping for many months. After surviving further convoy attacks he was promoted to 5th Officer in June 1944 and later that year obtained a 2nd Mate's Certificate. Less than a year later he was in Java when fighting broke out with the Indonesians and he again came under fire.

During 1949 and 1950 Captain White attended the University College of Southampton, School of Navigation, and obtained both a Master Mariner's Certificate and an Extra Master's Certificate. He was promoted to Chief Officer in the Royal Fleet Auxiliary in 1950 and then spent 18 months with the British forces involved in the Korean campaign.

From 1954 to 1955 he lectured at King Edward VII Nautical College, London but, preferring a more active life, returned to sea to command a geophysical survey vessel. By 1958 he had family commitments and decided, in his own phrase, 'to swallow the anchor'. He joined the Marine Survey Service of the Department of Trade as a nautical surveyor and examiner of Masters and Mates, taking up an appointment on the Central Board of Examiners in London. At this stage one of his tasks was to set and mark the examination papers for mariners on meteorology and oceanography. After three and a half years he was moved to surveying duties in Liverpool and in January 1965 was promoted and posted to Newcastle. In 1968 he was elected a younger brother of Trinity House.

On 1 November 1969 Captain White joined the Meteorological Office as Marine Superintendent. The following years have been difficult for all the merchant navies of the world as mercantile fleets have declined, and Captain White has worked tirelessly to maintain the quality of the liaison between the Office and the shipping industry. The main functions of the Marine Division for which he was responsible are to operate the United Kingdom Ocean Weather Ship (OWS), to recruit and maintain the Voluntary Observing Fleet, to obtain and archive high quality observations from the Voluntary Observing Fleet and to provide meteorological services to the shipping community including running a ship routeing service and answering marine enquiries.

From 1970 to 1977 Captain White was closely concerned with planning the future of the UK North Atlantic Ocean Station (NAOS) Ocean Weather Ships. After initial plans to replace the then-existing four Castle Class ships with purpose-built vessels were cancelled, it was decided to refurbish two of the 30-year-old existing ships. This major task was finally completed in 1977 when the ex-*Weather Monitor* sailed from Manchester as the 'new' OWS *Admiral Beaufort*. Captain White also took part in the protracted negotiations which led to the termination of the original International Civil Aviation Organization NAOS Agreement and its replacement by the existing NAOS Agreement under the auspices of the World Meteorological Organization. Later, during 1980 and 1981, he arranged for the sale of the OWS *Admiral Beaufort* and *Admiral FitzRoy* and the closing of the OWS Base at Greenock, when these were replaced in early 1982 by the single time-chartered OWS m.v. *Starella* which now sails from Fleetwood.

Throughout his time as Marine Superintendent, Captain White has maintained close and cordial relationships with the shipping industry both personally and through the efforts of his Port Meteorological Officers. This effort has been successful in maintaining the UK Voluntary Observing Fleet at over 500 ships in spite of the reduction in the total number of British merchant ships from over 3000 in 1970 to approximately 900 by the end of 1982.

Captain White has been Editor of the *Marine Observer*, a quarterly journal of maritime meteorology, which has as its main purpose the encouragement of a high standard of observing not only of meteorological conditions but also of a wide range of phenomena at sea. He has also been an active and well-liked member of the international marine meteorological community, where his sound and authoritative advice has led to invitations for him to act as the WMO representative at the Intergovernmental Maritime Organization Assemblies, on the Marine Safety Committee and on the Subcommittee on Safety of Navigation. He has also been principal delegate for the UK on the WMO Commission for Marine Meteorology and a member of the UK delegation to the NAOS Board.

Captain White is married and has three children. We wish him a long and happy retirement.

D. N. Axford

100 years ago

The following extract is taken from *Symons's Monthly Meteorological Magazine*, February 1883, **18**, 3.

A PALACE OF ICE.

WHILE the climate of England is oscillating between the close moisture of May, the bitter north-east winds of March, and the sleet and fog of November and December, Canada is rejoicing in the steady cold but bright and dry weather, upon the recurrence of which everyone in the Colony reckons, and reckons not in vain. Winter there is a source of great profit and of keen enjoyment. Without the regular frosts and dry snows with which the country is visited, half the work of the farm and of conveying the produce of the forests and the farm to market, would have to be left undone; and while the agriculturalist and the lumberer look forward to the advent of a steady "cold spell" — to say nothing of the opportunity that is afforded of laying up a store of ice for summer use — the people generally are not slow to avail themselves of the pleasure of sleighing, skating and tobogganing. This year the citizens of Montreal have inaugurated a new institution in the shape of a magnificent "Crystal Palace," which has been erected in Dominion Square in that city. Instead of glass and iron, ice is the material of which this building is constructed. Slabs of ice from the St. Lawrence, 40 inches high and from 14 to 20 inches in breadth and height, are the "bricks"; and these crystal blocks, piled on one another, are cemented together by a spray of water poured over them, which froze as it fell, and bound the whole together in a homogeneous mass. Of such material has a huge transparent palace been built, measuring nearly 100 feet square in the

interior, with walls 25 feet high, and with towers 15 feet square and 30 feet in height; while from the centre rises a massive tower 32 feet square and 100 feet high. The roof is constructed of rafters of wood, upon which were spread cedar branches; these, again, being cemented together, like the walls of the structure, by a spray of water, which froze them into a solid mass, with long icicles depending from the roof in most picturesque confusion. When the bright sun falls upon this glittering palace with its frosted roof, the effect is indescribably beautiful; while at night, illuminated with thousands of electric lights within and without, the spectacle is, if possible, of even greater brilliancy.

Printouts of weather data

Following the cessation of the *Daily Weather Report* at the end of 1980, and at the request of a number of organizations, the Meteorological Office has produced retrospective printouts of the coded synoptic messages for the 50 stations which used to feature in it. Since January 1982, when the new international synoptic codes were introduced, the output has been modified to present the information in a semi-plain language format. This was partly to save users the trouble of learning the new codes and partly because the inceased variability of the synoptic messages created difficulties in formatting. The printouts are now available on paper or microfiche. The current changes (exclusive of VAT) for microfiche are £4.75 per week, £12.00 per month and £32.00 per quarter whilst paper output is available on a weekly basis at £6.10. Universities and other educational establishments may apply for reduced rates.

Tabulated upper-air data, similar to those which appeared in the *Daily Aerological Record,* could also be made available. Requests for data or for further information on these services should be addressed to:

The Director-General
Meteorological Office, Met O 3
London Road
Bracknell
Berkshire RG12 2SZ

Requests for daily synoptic information in chart form, should be addressed to:

Principal Meteorological Officer
London Weather Centre
284–286 High Holborn
London WC1V 7HX

Honour

In the Birthday Honours list for 1982 it was announced that Mr F. A. Gordon (Professional and Technology Officer III) of the Meteorological Research Flight had been awarded the British Empire Medal.

Obituary

We regret to record the death on 19 September 1982 of Mr A. E. Radford, Assistant Scientific Officer, as a result of a traffic accident in France. Alan Radford joined the Office in August 1978, and had spent all his brief career at Gatwick Airport.

He was a motor sport enthusiast, and also devoted much of his spare time to helping to run the youth club in the south Sussex village where he lived and had been brought up.

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CONTENTS

An aircraft encounter with a tornado. W. T. Roach and J. Findlater 29

COMPSTAT 82. R.C. Tabony 49

Notes and news

Retirement of Captain G.A. White 50

100 years ago 51

Printouts of weather data 52

Honour 52

Obituary 52

NOTICES

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